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# MICROPROCESSOR CONTROL SYSTEM FOR 200-KILOWATT MOD-OA WIND TURBINES

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## SUMMARY

The microprocessor system and program used to control the operation of the 200-kW Mod-OA wind turbines is described. The system is programmed to begin startup and shutdown sequences automatically and to control yaw motion. Rotor speed and power output are controlled with integral and proportional control of the blade pitch angle. Included in the report are a description of the hardware and a discussion of the software programming technique. A listing of the PL/M software program is given in an appendix, which is contained on microfiche at the end of the report.

## INTRODUCTION

As part of the Federal Wind Energy program sponsored by the Department of Energy (ref. 1), NASA Lewis Research Center engineers designed and had installed four Mod-OA wind turbines. These wind turbines are located in Clayton, N. Mex; on the island of Culebra, Puerto Rico; on Block Island, R.I.; and on the island of Oahu, Hawaii. The Clayton machine is shown in figure 1. The Mod-OA wind turbines are first-generation two-blade, horizontal-axis machines that are designed to produce 200 kW of electric power at wind velocities of 9.8 m/sec (22 mph) or greater. (All wind velocities referred to in this report are measured at hub height.) These machines are controlled with a microprocessor system and have accumulated together more than 33 000 hours of running time. This report describes the control system presently used to operate these machines. Included are a description of the machine and control system, a description of the control program, a description of the system hardware, and a general description of the software as well as some of the programming methods used in the software. The complete program is given in an appendix, which is contained on microfiche at the end of the report. The microprocessor control system initially used to operate these machines is described in reference 2.

## DESCRIPTION OF MOD-OA WIND TURBINE

The Mod-OA wind turbine is a large horizontal-axis, two-blade machine. All mechanical components of the Mod-OA machines are located in a nacelle on top of a 28.3-meter (93-ft) tower. A schematic drawing of the nacelle interior is shown in figure 2. Two 19-meter-long blades (making a 125-ft-diameter rotor) are designed to rotate at 40 rpm and are attached to the hub pitch-actuator assembly. The pitch actuator controls the blade pitch angle under the direction of the microprocessor. The hub pitch-actuator assembly is connected to the low-speed shaft, which is supported on the bedplate by two large

bearings. The low-speed shaft drives a gearbox whose output shaft rotates at 1800 rpm. The output shaft is connected to the generator through a fluid coupling, a high-speed shaft, and a set of V-belts. A disk brake is also connected to the gearbox output shaft and is used for emergency stops and to lock the rotor during maintenance procedures. The hydraulic pump is located in front of the generator and supplies hydraulic fluid to the pitch actuator through the center of the low-speed shaft by use of concentric flow lines and rotating couplings. The electrical control signals for the pitch actuator are also brought through the low-speed shaft by means of a set of slip rings located near the gearbox. The nacelle is positioned about the vertical axis (yaw axis) by a yaw drive system. When not yawing, the nacelle is rigidly held to the tower by three yaw brakes. A set of yaw slip rings is used to connect the nacelle electrically to the control room located at the base of the tower.

The operation of the machine (i.e., startup, synchronization, power output, and shutdown) is automatically controlled by a microprocessor system. During operation the microprocessor adjusts the blade pitch, controls the rotor speed, and controls the power generated by the machine. For startup the blade pitch angle is set to  $-20^\circ$ . (By definition  $-90^\circ$  is full feather position and  $0^\circ$  is full power position.) When the rotor speed reaches 6 rpm, the pitch angle is changed to  $-5^\circ$  until 25 rpm is attained. At 25 rpm the microprocessor goes into speed control and the rotor speed is increased to 40 rpm. At 40 rpm the generator is automatically synchronized to the utility network when the generator and network voltages are in phase. After synchronization the microprocessor is placed in power control, during which the blade pitch angle is continuously adjusted to maintain an average output of 200 kW. When the wind velocity is not sufficient to produce 200 kW, the blade pitch angle is held at  $0^\circ$ , at which value the machine output power is maximum for wind velocities less than rated. When shutting down the machine, the pitch angle is decreased slowly until the machine starts motoring (negative power), at which time the generator is disconnected from the utility network. Then under speed control the rotor speed is decreased slowly from 40 rpm to 20 rpm. At 20 rpm the blades are pitched back to  $-90^\circ$  and the machine is completely shut down.

#### MICROPROCESSOR CONTROL

A microprocess system automatically controls the operation of the machine. During the startup, synchronization, and shutdown sequences the microprocessor adjusts the blade pitch angle to control rotor speed. Also, the blade pitch angle is adjusted to limit output power to 200 kW when the wind velocity exceeds 9.8 m/sec. The yaw motion of the nacelle is also controlled by the microprocessor.

Overall, the microprocessor is programmed to perform the following five primary functions so as to control the operation of the machine:

- (1) Monitor wind and power output to begin startup and shutdown (S/S) sequences when S/S wind and power criteria are met.
- (2) Control machine yaw motion so as to minimize yaw error.

- (3) Control rotor motion during startup, power generation, and shutdown sequences.
- (4) Monitor machine operating parameters to insure operation within safe limits.
- (5) Control displays and keyboard terminal; run timers and counters.

Each of these functions is described in the following paragraphs. The techniques discussed and the values of parameters used in the program to control the machine's operation have developed over a period of time and are based on operating experience.

#### DESCRIPTION OF MICROPROCESSOR PROGRAM

Figure 3 is a schematic diagram of the control system showing the microprocessor and the various input and output (I/O) signals used to control the machine. The safety system monitors various machine transducers and is able to shut down the machine independently of the microprocessor. As shown in the figure the microprocessor accepts eight analog and four discrete input signals and controls the machine with one analog and seven discrete output signals.

##### Analog Inputs

Wind velocity. - The wind velocity is measured with a propeller type of transducer mounted as part of a wind vane. This transducer is mounted on top of the nacelle and can be seen in figure 1.

Yaw error. - The yaw error is measured with the wind vane and is defined as the angle between the incoming wind direction and the nacelle longitudinal axis. The yaw error is zero when the nacelle longitudinal axis is aligned directly into the wind.

Redundant wind velocity. - The redundant wind velocity is measured with a second propeller type of transducer, which is also shown in figure 1. The transducer is rigidly mounted to the top of the nacelle and in line with the nacelle longitudinal axis. Therefore it measures the wind velocity along the axis of the nacelle. A large difference between the two wind velocity measurements indicates the possible existence of a large yaw error or of a problem with the velocity transducers.

Rotor speed. - The rotor speed is measured by a transducer that is mounted on the generator and that actually measures generator armature rotational speed. This measurement is not an absolute measure of the rotor speed, as some slip occurs in the V-belts and the fluid coupling. However, for control purposes this measurement of rotor speed has been adequate.

Pitch angle. - The blade pitch angle is measured with a transducer located on the hub pitch-actuator assembly. The pitch angle is defined as  $0^\circ$  when the blades are in full power position (as shown in fig. 1) and as  $-90^\circ$  when the blades are in full feather position. The pitch angle is also used as a feedback signal to the pitch angle controller. As such, it is compared with a pitch command (PITCHCMD) to produce proportional control of the hydraulic valves in the pitch actuator.

Power generated. - The power generated is measured with a Hall effect three-phase power transducer and is used for controlling output power and for display purposes.

Nacelle direction . - This input gives the compass heading of the nacelle. It is used only for display purposes; and when the yaw error is zero, it provides a measure of wind direction.

Power set point. - The maximum output of the machine can be controlled to any value less than 200 kW depending on the voltage applied to this input.

#### Discrete Inputs (ac Voltages)

Circuit breaker closed. - This input indicates that the circuit breaker (CB2, fig. 3) is closed and that the generator is connected to the utility system network.

Pitch pressure OK. - This input is obtained from a pressure switch that closes when the pitch hydraulic pressure is high enough to pitch the rotor blades.

Safety system shutdown. - This input indicates that an unsafe operating condition has been detected by the safety system. A safety system shutdown automatically enables the fail-safe valves. (The operation and purpose of the fail-safe valves are discussed later in this report.)

Brake on. - This input indicates that the disk brakes have been applied. It is obtained from a pressure switch located in the pneumatic brake system.

#### Analog Output - Pitch Command (PITCHCMD)

This signal is developed by the microprocessor during control operations and is the set-point voltage supplied to the pitch angle controller.

#### Discrete Outputs (ac Relay Contact Closures)

Safety system reset. - This output is used to reset the safety system after it has detected an out-of-tolerance condition. The safety system and the use of this output are described briefly later in this report.

Pitch pump on. - This output turns the pitch hydraulic pump on.

Failsafe disenable. - This output disenables the fail-safe valves and allows the blades to pitch under control of the pitch controller. The fail-safe valves are located between the pitch controller servovalve and the pitch actuators. When enabled, the fail-safe valves block the flow from the servovalves to the pitch actuators and connect the hydraulic supply and return lines to the actuators in such a manner as to force the blades to feather position. Thus the blades automatically return to the feathered position independently of the pitch controller and/or microprocessor system when these valves are enabled. Loss of control power, a safety system shutdown, or over-speed conditions will enable the fail-safe valves.

Generator field on. - This signal turns the generator field on.

Synchronization enable. - This signal enables the synchronizer to close the circuit breaker (CB2) when the synchronizer determines that the generator and utility network voltages are within phase and frequency tolerances for synchronization. When the synchronizer is disabled, CB2 will be open and the generator will be disconnected from the power line.

Clockwise and counterclockwise yaw. - These signals activate the yaw drives in the clockwise or counterclockwise direction.

Table I summarizes the rates at which analog inputs are measured and also indicates what calculations are performed on each input. Wind velocity, redundant wind velocity, and yaw error are measured once per second. The power is measured eight times per second as is the yaw error when the machine is yawing. In addition, each of the latest 64 wind velocity and power-generated measurements are classified according to the range of wind velocity or power level within which they fall. This classification is used in determining when to start up and shut down the machine, as discussed in the next paragraph. For the measurements indicated, a true average of the latest 64 measurements is calculated and used to provide filtering of the input signals. No electrical filtering is done on any of the analog signals. When testing for the existence of discrete input signals, the input signal of interest is checked at least twice and must exist for a minimum of 0.25 sec to insure the validity of the input. Both the analog and discrete output signals are updated 64 times per second.

#### Wind and Power Criteria for Startup and Shutdown

Once the automatic control system is enabled, the microprocessor is programmed to start the machine when 90 percent of the last 64 measurements of wind velocity are greater than 4.4 m/sec (10 mph) and the yaw error is less than  $\pm 25^\circ$ . Shutdown is begun when 50 percent of the output power measurements are less than -10 kW (motoring power) or 10 percent are less than -30 kW. The machine will also be shut down when 10 percent of the wind velocity measurements are greater than 17.9 m/sec (40 mph). After a 17.9-m/sec shutdown the machine is restarted after 90 percent of the wind velocity measurements are less than 15.6 m/sec (35 mph) for 10 consecutive minutes. The startup and shutdown criteria are summarized as follows:

- (1) For startup
  - (a) 90 percent of wind velocity measurements are greater than 4.4 m/sec (10 mph)
  - (b) After 17.9-m/sec (40-mph) shutdown, 90 percent of wind velocity measurements are less than 15.6 m/sec (35 mph) for 10 consecutive minutes.
- (2) For shutdown
  - (a) 50 percent of power measurements are less than -10 kW (motoring power)
  - (b) Or 10 percent of power measurements are less than -30 kW (motoring power)
  - (c) Or 10 percent of wind velocity measurements are greater than 17.9 m/sec (40 mph).



## Yaw Control

The yaw control is set up to keep the machine aligned into the wind in order to maximize energy capture. Maximum energy capture occurs when the machine is positioned such that the plane of rotation of the blades is perpendicular to the wind direction. The yaw control is enabled at all times when wind velocity is greater than 4.4 m/sec or when the machine is running. After the yaw control is enabled and the S/S criteria are met, yaw correction occurs whenever the average yaw error exceeds  $25^\circ$  in either direction. Also yaw correction will start if the average yaw error is greater than  $7^\circ$  in either direction for more than 5 consecutive minutes. The yaw drive is turned off when the average yaw error is within  $\pm 1^\circ$ . The  $7^\circ$  correction is disabled if the machine is generating more than 175 kW. During all yaw corrections a software timer is started to insure that the correction is completed within a nominal time period. When the nominal times are exceeded, the wind turbine is shut down and yaw fault is declared if the S/S criteria are still met. If the S/S criteria are not met, the yaw control is disabled and no fault is declared. Also the yaw control will be disabled if the system shuts down during a startup. The yaw correction criteria are summarized as follows:

- (1) 90 Percent of wind velocity measurements are greater than 4.4 m/sec (10 mph)
- (2) Average yaw error
  - (a) Greater than  $25^\circ$  in either direction
  - (b) Or greater than  $7^\circ$  in either direction

The amount of actual yawing a machine does during a week depends on site wind conditions and varies from 30 minutes to 2 1/2 hours with yaw corrections occurring from 10 to more than 300 times.

## Rotor Control

During the startup and shutdown sequences, the microprocessor operates in three different control modes. In the pitch control mode the program determines what pitch angle is required at any instant and puts this value out as the PITCHCMD. In the speed control mode the PITCHCMD is made proportional to the difference and time integral of the difference between an rpm command (RPMCMD) and the instantaneous rotor speed. Likewise in the power control mode the PITCHCMD is made proportional to the difference and time integral of the difference between a power command (PWCMD) and the instantaneous output power of the machine. Figure 4 illustrates the control modes and gives the values of gain used for the proportional and time-integral control components. These gains were obtained experimentally and are such as to maintain system stability during all wind conditions. How the proportional and integral parts of the PITCHCMD are generated is described in the software section.

In the paragraphs that follow, a fault test consists of shutting down the machine and testing to see if the S/S criteria are still being met. If the shutdown criteria are not being met (i.e., the wind velocity has dropped off), the machine is enabled to restart. Otherwise a fault is declared, brought to the attention of the utility personnel, and the machine is disabled.

Startup sequence. - The startup sequence consists of the following events: turn on pitch hydraulic pump, pitch control to a rotor speed of 25 rpm, speed control from 25 rpm to 38 rpm, and 38 rpm to synchronization.

Turn on pitch hydraulic pump: After the wind criteria are met, the microprocessor enables the pitch-pump-on output and allows 2 min for the pitch-pressure-OK switch to close. If the pressure switch does not close within this period, the pump is turned off and a pitch pressure fault is declared. If the pressure is achieved, the startup sequence continues.

Pitch control to a rotor speed of 25 rpm: The microprocessor is set up initially for pitch control. The pitch angle is changed at a constant rate (ramped) of 3.2 deg/sec until a pitch angle of  $-20^{\circ}$  or a rotor speed of 6 rpm is attained. If 6 rpm is not attained within 2 min, a fault test is performed. When 6 rpm is attained, the pitch angle ramp rate is changed to 0.8 deg/sec until a pitch angle of  $5^{\circ}$  or a rotational speed of 25 rpm is attained. If 25 rpm is not reached within 2 min, a fault test is performed.

Speed control from 25 rpm to 38 rpm: When 25 rpm is attained, the microprocessor is shifted to speed control, and the RPMCMD is ramped at a rate of 0.4 rpm/sec to 39.75 rpm. If during this ramp the rotor speed lags the RPMCMD by more than 1 rpm, the ramp rate is reduced to 0.2 rpm/sec. If the rotor speed lags the RPMCMD by more than 2 rpm, the ramp is halted. If at any time the rotor speed lags the RPMCMD by more than 3 rpm for 15 sec, a fault test is performed. A test is also made for rotor speeds greater than the RPMCMD + 5 rpm. If this condition occurs, a pitch fault is declared and the machine is shut down.

38 rpm to synchronization: At a rotor speed of 38 rpm the generator field is turned on with the generator-field-on discrete output, and at 39.75 rpm the synchronization-enable discrete output is activated. The synchronizer closes CB2 independently of the microprocessor when the phase angle between the generator voltage and the network voltage is between  $-10^{\circ}$  and  $+10^{\circ}$  for 0.2 sec. In order to achieve synchronization, the RPMCMD is cycled between 39.75 and 40.25 rpm at a ramp rate of 0.0125 rpm/sec (80 sec/rpm). This slowly varying rotor speed allows the phase angles of the generator and network voltages to meet the synchronizer requirements. This cycle is repeated three times. During the time required for the three cycles, the generator and utility system should be in phase properly five times over a 200-sec time period. If synchronization is not achieved after the three ramp cycles, a fault test is performed.

Power generation. - The microprocessor tests to determine if synchronization is achieved by continuously monitoring the circuit-breaker-closed switch. When this switch has been closed continuously for 0.25 sec, the microprocessor assumes the wind turbine has synchronized and goes into power control. The PWCMD is ramped at a rate of 9.3 kW/sec until either a 200-kW value or that value determined by the power set point is attained.

Shutdown sequence. - The machine will shut down when the shutdown criteria are met. At this time the microprocessor opens the synchronization-enable relay switches to speed control and ramps the RPMCMD from 40 rpm to 20 rpm at



a rate of  $-0.4$  rpm/sec. At 36 rpm the generator-field-on relay is opened. When 20 rpm is attained, the microprocessor switches to pitch control and the pitch angle is ramped at a rate of  $-0.8$  deg/sec. When the pitch angle is  $-30^\circ$ , the pitch ramp changes to  $-3.2$  deg/sec. The fail-safe valves and the hydraulic pump are turned off when the pitch angle is  $-90^\circ$ . If utility personnel or high wind conditions initiate a shutdown while the turbine is still on line, the microprocessor first goes into pitch control and then ramps the pitch angle at a rate of  $-0.8$  deg/sec. When the power output reaches zero, the microprocessor opens the synchronization-enable output, shifts to speed control, and shuts down as just described. If a wind gust causes the rotor speed to exceed 41 rpm at any time while shutting down, a switch is made to pitch control and the pitch angle is ramped at a rate of  $-3.2$  deg/sec until 40 rpm is attained. At this time, a switch is made back to speed control and the system proceeds to shut down as previously described.

Typical startup and shutdown sequences. - Figures 5 and 6 are included to show typical strip-chart data recorded during startup and shutdown sequences. In both figures, wind velocity, pitch angle, rotor speed, and power output are shown as a function of time. (Time = 0 is arbitrary in these figures.) Figure 5 shows the sequences for a low-wind-speed start, when the wind velocity just meets the startup criteria. The pump has been turned on and the blades have begun to pitch at  $3.2$  deg/sec. At 42 sec the blades are at  $-20^\circ$  and the pitch is held constant at this point. At 54 sec the rotor has achieved 6 rpm. The pitch angle then increases to  $-5^\circ$  at a rate of  $0.8$  deg/sec. It holds at this value until a rotor speed of 25 rpm is attained, after which the RPMCMD ramp is started. The pitch angle can be seen to vary while control of rotor speed is being maintained. At 130 sec the machine is synchronized and the power starts to increase. Because the wind speed is low, the blade pitches to  $0^\circ$  and the output power follows the wind velocity. The time required to synchronize is approximately 110 sec from the time when the blades started to pitch. At 320 sec the power has reversed and the shutdown criteria are met. The rotor speed ramps down under controlled conditions until 20 rpm is reached at 370 sec. At this time the microprocessor switches to pitch control and ramps the blade pitch angle at  $-0.8$  deg/sec until, at 392 sec, the pitch angle is  $-30^\circ$ . The blade pitch angle ramp is increased to  $-3.2$  deg/sec and the machine completes the shutdown.

A high-wind-speed startup is shown in figure 6. In this example, the wind is approximately 13.4 m/sec (30 mph) and the wind turbine has been shut down because of high winds. The sequence is the same as in the preceding example, but in this case, the 6- and 25-rpm rotor speeds are rapidly attained. At 25 rpm the microprocessor switches to speed control and synchronization is achieved at 120 sec. In this case the machine took 100 sec to synchronize from the time the blades started to pitch. After synchronization the PWCMD is ramped up and since the wind speed is high, the pitch angle varies with the wind velocity, holding the average power to 200 kW.

#### MACHINE-OPERATIONS MONITORING

A number of tests are continuously performed by the microprocessor to insure that the machine is operating within design tolerances. If the machine is operating out of tolerance, the microprocessor begins shutdown under con-

trolled conditions that do not overstress machine components. The following tests are performed:

#### 42-RPM Overspeed

Tests are made to determine if the rotor speed exceeds 42 rpm at any time. If the speed exceeds 42 rpm, the microprocessor will activate the fail-safe valves to shut down the machine.

#### Safety System Shutdown

As indicated previously, the wind turbine is designed with a safety system that monitors such operating conditions as component temperatures, blade strains, hydraulic fluid pressures, various gas bottle pressures, rotor overspeed, and machine vibration levels. If any of these measurements are found to be out of tolerance, the safety system puts out a signal detected as a safety system shutdown. As stated previously, the safety system also shuts down the machine independently of the microprocessor by disabling the fail-safe valves.

#### In-Synchronization Test

The microprocessor tests to determine if the machine is maintaining synchronization by monitoring the circuit-breaker-closed input. If synchronization is lost during running by an overcurrent, for example, which independently will open CB2, the microprocessor detects this fault and proceeds to shut down the machine.

#### Rotor Speed Less Than 38 rpm

Operational experience has shown that it is desirable to test for rotor speed indications of less than 38 rpm while the machine is synchronized. Since the rotor speed should be 40 rpm, a speed indication of less than 38 rpm means a speed transducer problem and the machine is shut down.

#### Delta Velocity Error ( $\pm 4.4$ m/sec)

In this test the difference in the wind velocity and redundant wind velocity measurements is calculated as a check on the machine yaw and also on the transducers. A large yaw error would show up as a large difference in the two readings. Also if a transducer fails, a large difference would also be expected.

#### Power Station Breaker

This test gives an indication that the utility system is ready to accept power from the wind turbine.

#### Pitch Pressure

The pitch pressure switch is monitored at all times after the blades start pitching. This insures that there is an adequate supply of pitch hydraulic

fluid for the pitch actuator system. If pressure drops below the pitch-pressure-switch opening level, shutdown is begun.

### Brake On Test

The microprocessor tests to determine if the rotor brake is activated at any time. The only time the brake is activated is when an independent over-speed switch detects that the rotor speed exceeds 45 rpm. When this occurs and the brake is set, utility personnel must visit the site to reset the brake.

### DISPLAYS, TERMINAL, TIMERS, AND COUNTER CONTROLS

The microprocessor, display system, and keyboard terminal are shown in figure 7. The microprocessor system is enabled for automatic control by pressing the START button on the front panel. Pushing the STOP button begins shutdown, which, when complete, results in automatic control being disabled. During the startup sequence the machine can be shut down by pushing the STOP button. When shutting down, the machine can be restarted at any point in the startup sequence with the START button. The machine can also be enabled and disabled by a remote controller, not shown in the figure, and also from the keyboard terminal. In Clayton and Block Island, the remote controller is located in the powerplant, less than a mile away, and is connected by dedicated data lines to the wind turbine site. In Puerto Rico, the remote controller is located near San Juan, some 50 miles away, and is connected by radio link to the Culebra wind turbine site. Hawaii uses dedicated phone lines between the wind turbine site and Honolulu, 50 miles away. The keyboard terminals are all located at the turbine sites, except at Culebra, where it is connected by dedicated phone lines to the small backup powerplant on the island.

The display built into the microprocessor front panel shows the status, pitch angle, average wind velocity, average redundant wind velocity, average yaw error, nacelle direction, rotor speed, and average power output. All of these readings are in engineering units. The status display is used to indicate the operating state of the turbine. It is also used to indicate the particular fault detected during operation. Table II lists the status codes and what they represent. The status is also displayed on the remote controller and is printed on the terminal for record purposes. The status is a two-digit number and typically will be either a 08 or a 00 when the microprocessor is turned on. When the machine is enabled and in the starting sequence, the status will change to 11, 12, 13, 14, 15, or 16 as the machine starts up and synchronizes.

When a fault is detected, the status code is displayed. If more than one fault occurs, each is held in memory until the START button is pressed. Then each fault in reverse order of occurrence (i.e. last in, first out) is displayed with each push of the START button. When all faults have been displayed, the next start enables the control system. If three faults occur in succession with no synchronizations in between, the machine is not allowed to start and must be reset at the site with the RESET button on the microprocessor front panel. Each time a status changes, it is printed on the terminal.

The utility personnel have two options available to them when running the machines. These options are enabled through use of the thumbwheel switches on the microprocessor console card. The first option allows the machine to operate at reduced output power controlled by the power-set-point analog input. The second option enables the microprocessor to automatically reset system faults. When the second option is enabled and the machine is shut down as a result of a fault, the program generates START commands and safety system resets at 1-min intervals until all faults have been processed. This action is the same as if someone were pushing the START button, as described previously, and manually resetting the safety system. After all faults have been processed, the control system is again enabled for automatic operation.

The microprocessor controls four hourmeters and four mechanical pulse counters that are used in gathering operational data. The hourmeters measure total yaw time, synchronization time, wind available time (that time when wind is greater than 4.4 m/sec), and outage time (that time when the machine is disenabled). Three pulse counters give measures of total wind energy available, energy available during startup and shutdown, and outage energy. These energies are calculated by assuming a linear relationship between power and wind velocity with 0-kW output at 4.4 m/sec and 200-kW output at 9.7 m/sec (22 mph). The fourth counter indicates total energy generated as determined from the average of the power-generated measurement.

To match machine operating characteristics to site wind conditions and/or to compensate for configuration changes, a number of operating parameters were made site-dependent variables. These parameters include startup wind velocity, nominal yaw times, and various parameters required to change rotor speed. At two sites, the rotor speed has been reduced to 31.5 rpm to better match the machine to site wind conditions. This speed change is accomplished by changing the pulleys on the V-belt drive. This rotor speed change also requires changes in all the parameters in the startup sequence that are rotor speed dependent. By use of site-dependent variables the main microprocessor program remains the same at all sites.

#### MICROPROCESSOR HARDWARE

The microprocessor system is made up of Control Logic's M-series modules and four NASA-designed special-purpose cards. The system uses an Intel 8080 eight-bit parallel microprocessor and is wired with one teletype interface and seven interrupts. Included as M-series components are the following:

- (1) One 16-channel multiplexed analog-to-digital (A/D) converter with  $\pm 10$ -V dc inputs and 12-bit resolution
- (2) Twelve 120-V ac discrete inputs (only four used)
- (3) Eight 120-V ac, 2-A discrete outputs (relays)
- (4) One two-channel digital-to-analog (D/A) converter with  $\pm 10$ -V output
- (5) One 4-kilobyte RAM (random access memory)
- (6) One 16-kilobyte EPROM (erasable programmable read-only memory) (14 kilobytes used)
- (7) One terminal interface card
- (8) One EIA RS 232 interface card

In addition, the special-purpose cards provide for

- (1) Eight normally open (NO) relay contacts for dc signals
- (2) One 64-Hz clock oscillator combined with a 50-msec resettable timer (WATCHDOG TIMER)
- (3) One display interface
- (4) One site selection card

The display is software controlled and is set up to multiplex 16 two-digit numbers by using two output selects. One select addresses the two digits to be displayed. The second is used to latch the data into the display.

#### MICROPROCESSOR SOFTWARE

The software program was written in Intel's High Level Programming Language for Microprocessors, PL/M, and is compiled on the Lewis Research Center's IBM 370/3033 general-purpose computer. To aid in program development, a hardware input/output (I/O) simulator is used in conjunction with a microprocessor chassis for debugging purposes. The program is downloaded from the IBM 370/3033 directly into the simulator and debugged with Control Logic's Octal Debugging Technique (ODT) program. The EPROM's are programmed with a PROM programmer incorporated as part of the simulator system.

A listing of the PL/M program is given in the appendix (microfiche). Procedures are the PL/M version of subroutines, which are called at various times while the program is running. The appendix includes a list that groups the procedures used in performing the function previously described. The PL/M program is arranged as required by the compiler with the variables defined first, followed by the interrupt procedures, the set of procedures called throughout the program, initialization statements, and the operating part of the program.

Figure 8 gives a simplified flow diagram of the software program. The first executable statements occur in the INITIALIZATION section, wherein all flags are set and variables are given their starting values. This includes those parameters that are site dependent. The program then proceeds to cycle through the OPERATE section. The following general discussion of the program covers system timing, PITCHCMD generation, and terminal and display control.

#### System Timing

The program is set up in a sequence or cycle type of operation as opposed to an executive-ordered program. Three interrupts are used to set S/S and reset flags, which are later serviced by the INTERRUPT SERVICE procedure. The events in a given cycle are processed on a schedule that depends on system clock time. The system clock frequency is derived from a crystal-controlled 64-Hz oscillator (special-purpose card). In essence, the program runs through the operate portion of the program and waits in a loop in the CLOCK PROCEDURE until the oscillator sets a flipflop. When this set is detected, the program proceeds first to reset the flipflop and then to run through the remaining part of the program, ending up holding again in the CLOCK procedure. The program is designed such that no cycle lasts longer than one 64-Hz clock period.

Software counters are used to keep track of system clock time and are incremented each time the flipflop is reset. Procedures are scheduled to be processed at specific system clock times. Therefore not every procedure is processed during each cycle. The longest cycle is approximately 14 msec, and the average time is 9 msec out of the 15.4 msec for one period of the 64-Hz clock. In this way, time reference is maintained for the generation of the integral component of the PITCHCMD.

A 50-msec WATCHDOG TIMER is used as an independent check on the microprocessor operation. The WATCHDOG TIMER is reset each time the program runs through the operate cycle. The output of this timer is directly connected to the safety system; and if the 50-msec time lapses, the safety system will shut down the wind turbine. This is therefore an independent check on the microprocessor operation.

### Blade Pitch Control

The PITCHCMD is generated 16 times per second from the pitch angle commands RPMCMD and the PWCMD. As indicated previously, when in speed control or power control, the PITCHCMD consists of the sum of two components: a proportional component and an integral component.

$$\text{PITCHCMD} = P + I$$

where

P proportional part of PITCHCMD

I integral part of PITCHCMD

The proportional gain is obtained through shift-right and -left operations on the calculated difference between the RPMCMD and the rotor speed or the difference between the PWCMD and the instantaneous power generated. The proportional component for speed control is obtained with a single shift-left operation on the calculated difference. The proportional component for the power control is obtained by four shift-right operations of the power difference. The number of shift operations depends on the binary conversion factors and the gain required in the system. The integral component is calculated by summing the differences generated each time the CONTROL PROCEDURE is entered (16 times per second). When the sum reaches a certain value dependent on the binary conversion factors required, the integral portion of the PITCHCMD, I, is incremented or decremented one unit, and the sum is decremented or incremented by the gain value.

### Display and Terminal Control

Each of the displayed parameters is updated eight times per second. The binary numbers are converted to engineering units and processed to the displays by use of a lookup table. The lookup table is used for binary to decimal conversions and takes up 2 kilobytes of the EPROM memory. In all of the conversions, only right and left-shift operations are used rather than software multiplication and division.



Input/output services for the keyboard terminal are processed in the CLOCK PROCEDURE during the wait cycle. To eliminate timing problems, only one input or output is processed during each wait cycle. A software clock/calender is also included in the program, and the time and day numbers are printed each time the turbine synchronizes to the line and each time it goes off line. Also, a set of data including wind velocity, power, and status is printed once each hour. The control of the turbine from the terminal is described in table III.

#### CONCLUDING REMARKS

The microprocessor-based system described in this report controls the operation of the 200-kW Mod-OA wind turbines. It has been installed in four machines. These machines have accumulated more than 32 000 hours of operating time. The microprocessor program controls rotor speed and output power by controlling the blade pitch angle. Both proportional and integral control functions are generated by the software and used in the blade pitch control. Yaw control, system monitoring, and some operations data recording are performed by the microprocessor system. The use of a microprocessor has led to flexibility in the development of the control system for the Mod-OA wind turbines.

#### REFERENCES

1. Robbins, W. H.; Thomas, R. L.; and Baldwin, D. H.: Large Wind Turbines - A Utility Option for the Generation of Electricity. NASA TM-81502, 1980.
2. Gnecco, A. J.; and Whitehead, G. T.: Microprocessor Control of a Wind Turbine Generator. NASA TM-79021, 1978.

TABLE I. - OPERATIONS PERFORMED ON ANALOG INPUTS

PARAMETER	MEASUREMENT RATE, PER SECOND	CALCULATIONS	
		AVERAGE	CLASSIFICATION
WIND VELOCITY (VEL)	1	YES ↓	$VEL < 4.4 \text{ m/sec}$ $4.4 \text{ m/sec} \leq VEL < 15.6 \text{ m/sec}$ $15.6 \text{ m/sec} \leq VEL < 17.9 \text{ m/sec}$ $17.9 \text{ m/sec} \leq VEL$
POWER GENERATED (PW)	8		$PW < -30 \text{ kW}$ $-30 \text{ kW} \leq PW < -10 \text{ kW}$ $-10 \text{ kW} \leq PW$
YAW ERROR	a <sub>1</sub>		NONE ↓
REDUNDANT WIND VELOCITY	1	↓	
ROTOR SPEED	16	NO ↓	
PITCH ANGLE	64		
POWER SET POINT	16		
NACELLE DIRECTION	8	↓	↓

a<sub>8</sub> while yawing.



TABLE II. - STATUS CODE DEFINITION

NORMAL OPERATION

1ST DIGIT (LEFT MOST)

- 0 READY FOR START
- 1 START
- 2 STOP
- 4 YAW DRIVE OPERATING

2ND DIGIT (RIGHT MOST) WITH 1ST DIGIT READING BETWEEN 0 AND 2

- 0 WIND OK READY TO START
- 1 PUMP TURNED ON
- 2 0 - 6 rpm
- 3 6 - 25 rpm
- 4 25 - 38 rpm
- 5 38 - SYNC
- 6 NORMAL RUNNING (IN SYNC)
- 7 SHUTTING DOWN (OUT OF SYNC)
- 8 LOW WIND
- 9 HIGH WIND

MICROPROCESSOR DETECTED FAULTS

- 31 BRAKE ON
- 32 SAFETY SYSTEM SHUTDOWN
- 33 REDUNDANT SHUTDOWN
- 34 POWER STATION BREAKER OPEN
  
- 51 PITCH PRESSURE NOT OBTAINED AT STARTUP
- 52 START SEQUENCE FAULT
- 53 rpm LESS THAN RPMCMD - 3
- 54 SYNC NOT ACHIEVED BEFORE 3 CYCLES
- 55 rpm GREATER THAN RPMCMD + 5
  
- 61 YAW FAULT
- 62 PITCH PRESSURE LOW WHILE RUNNING
- 63 SYNC LOST DURING RUNNING RESULTING IN A 90 ON RESET
- 64 REDUNDANT YAW ERROR
- 65 DELTA VELOCITY ERROR
- 67 RPM OVERSPEED (OVER 42 RPM)
- 68 RPM UNDER 38
  
- 90 SAFETY SHUTDOWN 3 TIMES WITHOUT SYNC MUST RESET AT SITE

TABLE III. - TERMINAL CONTROL

TYPE (CNTRL)-X MEANS TO PRESS THE CTRL KEY AT THE SAME TIME AS THE LETTER.

TO START TURBINE FROM TYPEWRITER	TYPE (CTRL)-G
TO STOP TURBINE FROM TYPEWRITER	TYPE (CTRL)-S
TO HALT TURBINE	TYPE (CTRL)-H
TO SET MICRO CLOCK	TYPE (CTRL)-I
TO OBTAIN TYPED DATA SET	TYPE (CTRL)-D
TO OBTAINED A TYPED OUT TIME	TYPE (CTRL)-T

TO TYPE MESSAGE, JUST TYPE ANYTHING YOU MIGHT WANT AND THE SYSTEM WILL KEEP ON OPERATING AS IS. THE ONLY TIME SOMETHING SHOULD HAPPEN IS WHEN THE CONTROL KEY (CTRL) IS PRESSED AT THE SAME TIME AS ONE OF THE ABOVE LETTERS IS TYPED.

THE SYSTEM WILL PRINT OUT EVERY CHANGE IN STATUS THAT OCCURS.

THE SYSTEM WILL PRINT OUT EVERY HOURS ON THE HOUR THE TIME, DATA (WIND VEL., POWER) ALONG WITH STATUS

THE SYSTEM WILL PRINT OUT THE TIME WHEN EVER IT GOES ON LINE AND WHENEVER IT GOES INTO A SHUTDOWN AFTER BEING ON LINE.

TYPICAL TYPEWRITER OUTPUT WHEN POWER GOES ON OR WITH MICRO RESET.

08:00:.....

TYPICAL OUTPUT WITH A (CTRL)-I. (NUMBERS AFTER X'S WERE ENTERED BY USER)

DAY NUMBER XXX 015	*IF ERROR MESSAGE OCCURS, USER MUST START *
HOUR XX 14	*OVER WITH A (CTRL)-I. ERROR MESSAGE READS*
MINUTE XX 55	* "ERROR PLEASE TRY AGAIN" *

TYPICAL OUTPUT AFTER (CTRL)-D

D  
014 16:11 WIND SPEED = 15.0 POWER = 010 STATUS = 12

TYPICAL OUTPUT AFTER (CTRL)-1

T  
014 13:22

TYPICAL OUTPUT AFTER (CTRL)-G

G11:12:13:14:12:15:  
014 16:11 16:.....

TYPICAL OUTPUT AFTER (CTRL)-S

S  
014 16:12 27:20:.....

TYPICAL OUTPUT AFTER (CTRL)-H

H  
014 16:14 32:.....



Figure 1. - 200-kW Mod-0A wind turbine.

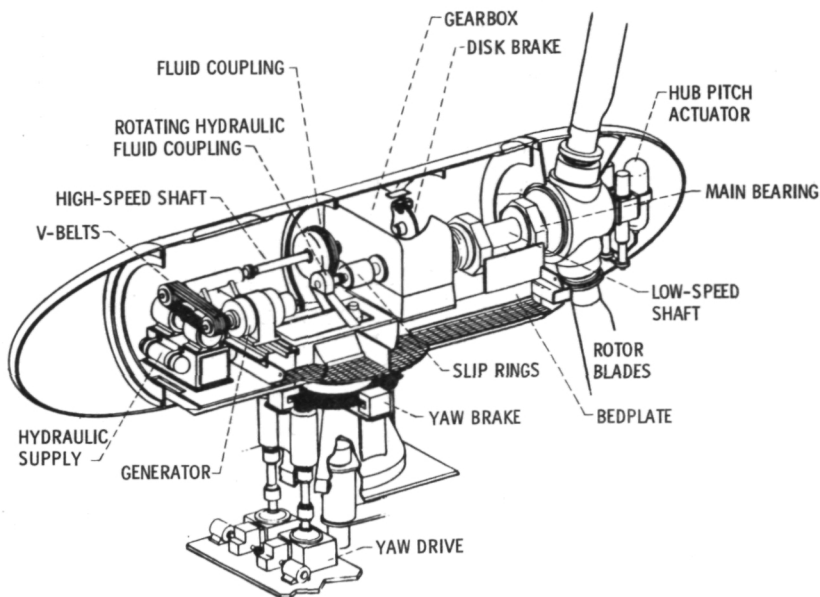


Figure 2. - Schematic of nacelle interior.

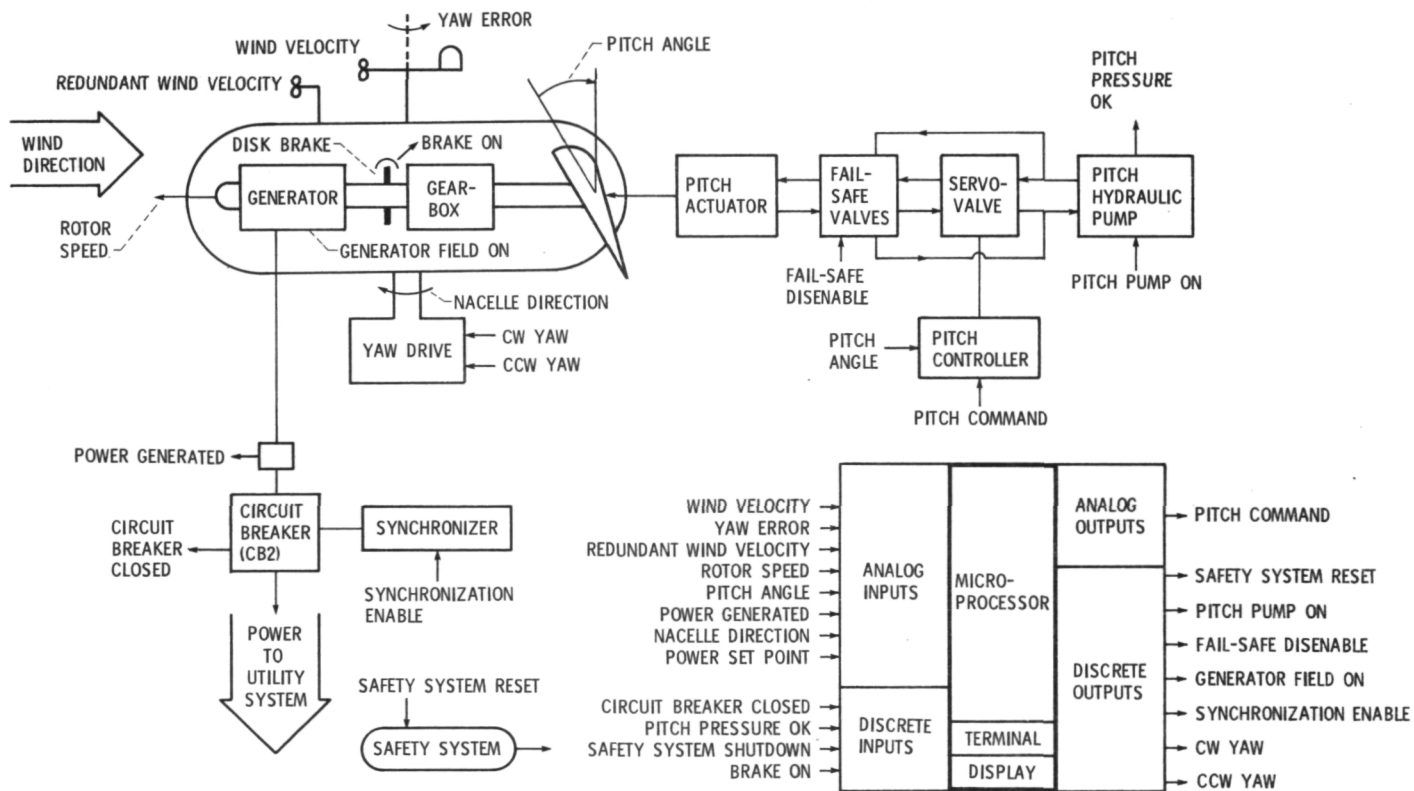


Figure 3. - Schematic diagram of Mod-0A microprocessor control system.

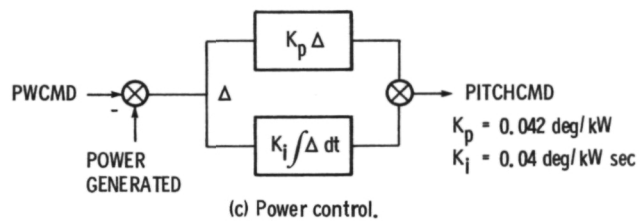
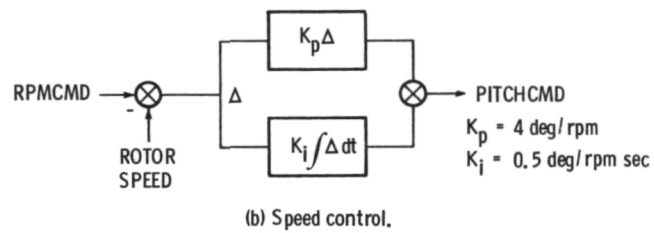
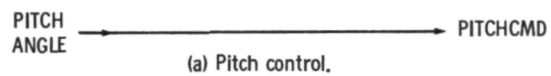


Figure 4. - Pitch command generation.

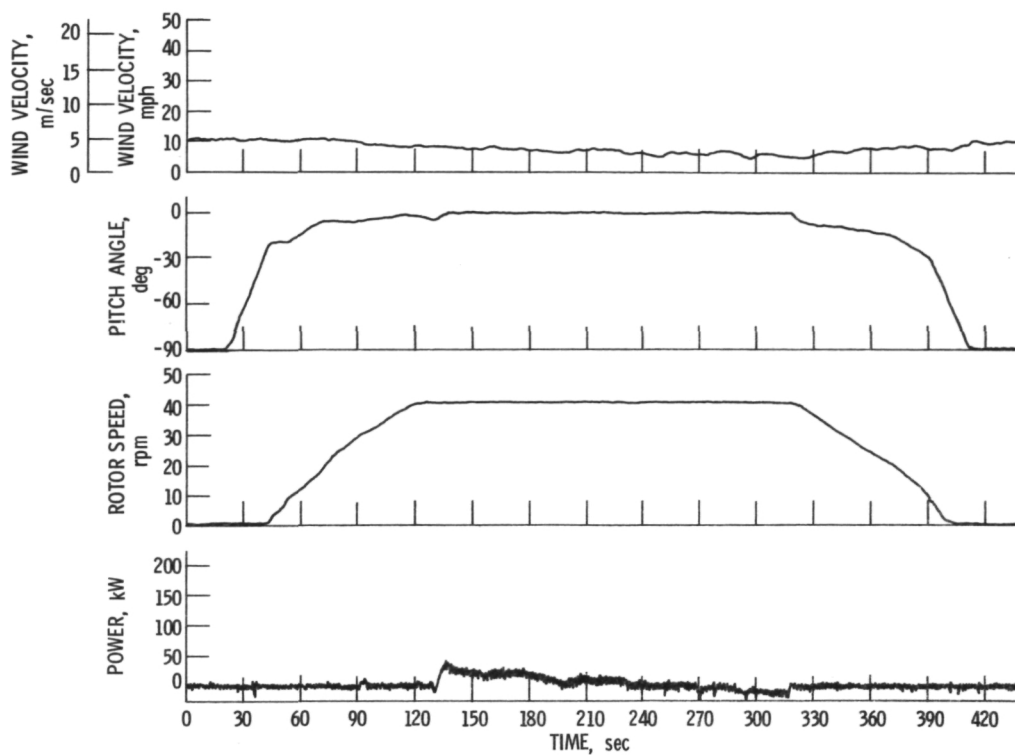


Figure 5. - Low-wind-speed startup and shutdown.

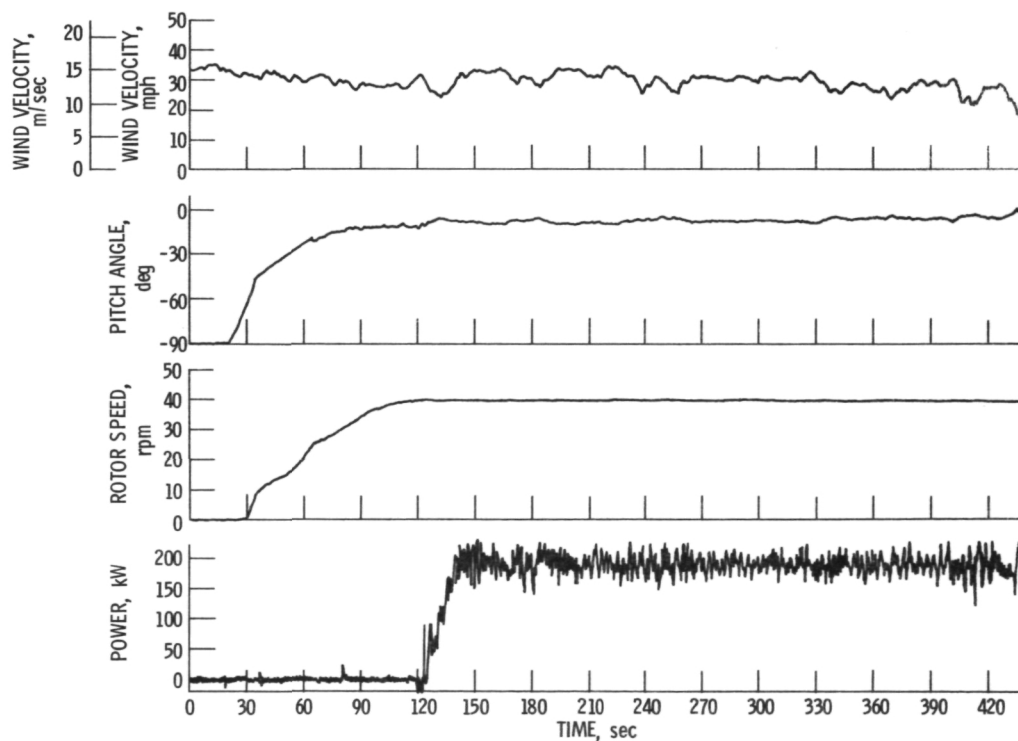


Figure 6. - High-wind-speed startup.

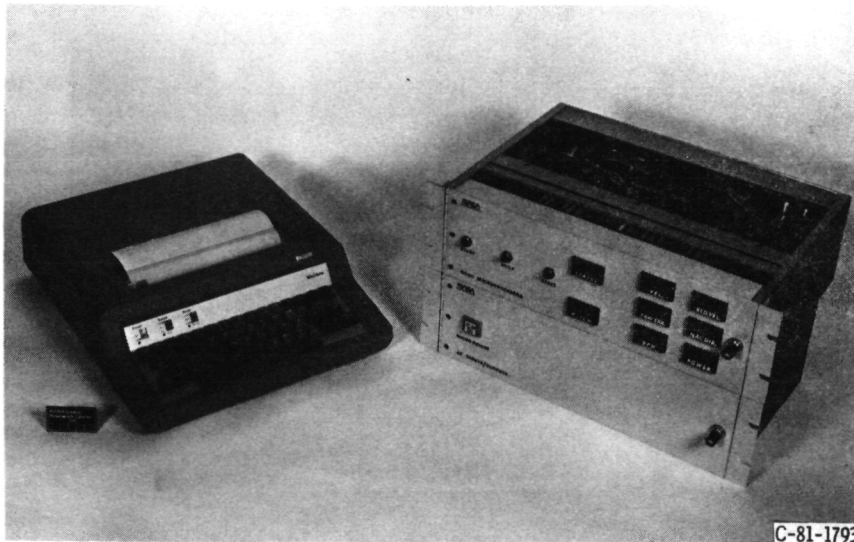


Figure 7. - Microprocessor and terminal.

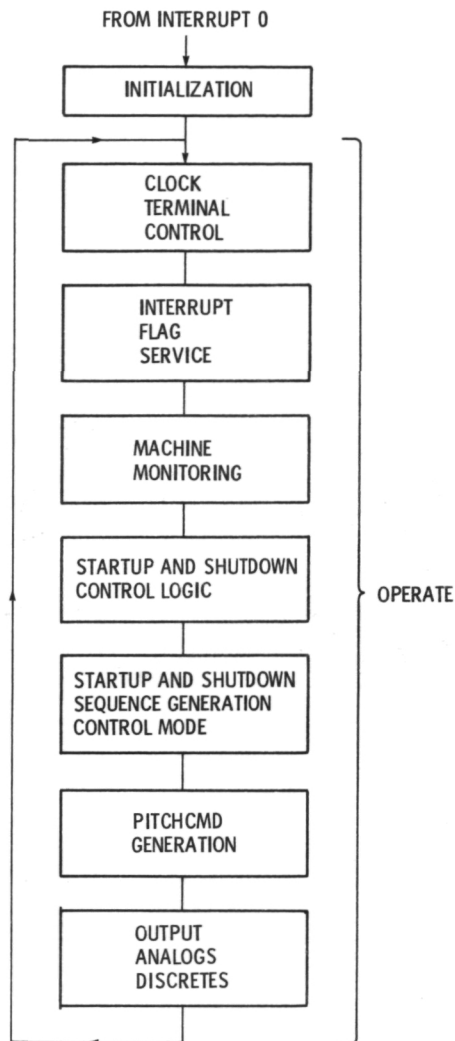


Figure 8. - Flow diagram for microprocessor software.



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16. Abstract The microprocessor system and program used to control the operation of the 200-kW Mod-0A wind turbines is described. The system is programmed to begin startup and shutdown sequences automatically and to control yaw motion. Rotor speed and power output are controlled with integral and proportional control of the blade pitch angle. Included in the report are a description of the hardware and a discussion of the software programming technique. A listing of the PL/M software program is given in an appendix, which is contained on microfiche at the end of the report.					
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